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Procedia - Social and Behavioral Sciences 48 (2012) 331 – 340

Procedia
Social and Behavioral Sciences

Transport Research Arena – Europe 2012

Life-cycle cost analysis system for pavement management

João Santos[a], Adelino Ferreira[a,*]

[a]*Department of Civil Engineering, University of Coimbra, Rua Luís Reis Santos, 3030-788 Coimbra, Portugal*

Abstract

This paper presents a new Life Cycle Cost Analysis (LCCA) system based on an optimization model considering pavement performance, called OPTIPAV, developed and programmed to help pavement designers to choose the best pavement structure for a road or highway. The LCCA system considers the serviceability concept adopted by the American Association of State Highway and Transportation Officials (AASHTO) for use in the design of flexible pavements. The OPTIPAV can solve the problem of making LCCA for typical design periods (20 years) but also for longer periods (40 years or more), in order to compare different pavement solutions in terms of global costs for the final choice of the pavement structure for a national road or highway. Additionally, the OPTIPAV system provides a good solution to the pavement design problem considering not only design criteria but also construction costs, maintenance costs, user costs and the residual value of pavement structures. The results obtained by the application of the new LCCA system clearly indicate that it is a valuable addition to the road engineer's toolbox.

Keywords: pavement design; life-cycle cost analysis; deterministic pavement performance models; pavement maintenance and rehabilitation; optimisation models; genetic algorithms.

1. Introduction

Despite the fact that the design period for flexible pavements is normally considered as 20 years, the Portuguese manual of pavement structures (JAE 1995) states the importance of making a Life Cycle Cost Analysis (LCCA) for a period of no less than 40 years, called project analysis period, in order to compare different pavement solutions in terms of global costs for the final choice of the pavement structure for a

* Corresponding author: Tel.: +351.239797101; fax +351.239797142.
E-mail address: adelino@dec.uc.pt .

doi:10.1016/j.sbspro.2012.06.1013

national road or highway. It also states that the following costs must be considered in the LCCA: construction costs; maintenance costs throughout the project analysis period; user costs throughout the project analysis period; and the pavement residual value at the end of the project analysis period. The problem is that until now this analysis has never been done in Portugal. This paper presents a new LCCA system based on an optimization model considering pavement performance, called OPTIPAV, developed and programmed to help pavement designers to choose the best pavement structure for a road or highway. The paper is divided into four sections. The first section consists of a brief introduction. The second section contains a detailed description of the OPTIPAV system. The third section presents the results obtained with the application of the OPTIPAV system to the pavement structures of the Portuguese Manual. The final section comprises a synthesis of the conclusions reached so far and a statement of prospects for future research.

2. Proposed Life-Cycle Cost Analysis System

2.1. Introduction

The proposed LCCA system, called OPTIPAV, consists of the following components: the objective of the analysis, the road pavement data and models, the constraints that the system must guarantee and finally the results. The OPTIPAV system was implemented using Microsoft Visual Studio programming language adapting and introducing new functionalities to an existing genetic algorithm program called GENETIPAV-D (Ferreira 2001, Ferreira et al. 2002) previously developed to solve deterministic optimization models. The results of the application of the OPTIPAV system consist of the optimal pavement structure, the predicted annual pavement quality, the construction costs, the M&R plan and costs, the user costs, and the pavement residual value at the end of the project analysis period.

2.2. Optimization model formulation

The optimization model introduced above can be formulated as follows:

$$\text{Min } CC_{s0} + \sum_{t=1}^{T} \sum_{r=1}^{R} \frac{1}{(1+d)^{t}} \times MC_{rst} \times X_{rst} + \sum_{t=1}^{T} \frac{1}{(1+d)^{t}} \times UC_{st} - \frac{1}{(1+d)^{T+1}} \times RV_{s,T+1} \quad (1)$$

$$Z_{st} = \Phi(Z_{s0}, X_{1s1},...,X_{1st},...,X_{Rs1},...,X_{Rst}), s = 1,...,S; t = 1,...,T \quad (2)$$

$$Z_{st} \begin{Bmatrix} \leq \\ \geq \end{Bmatrix} \overline{Z}, s = 1,..., S; t = 1,..., T \quad (3)$$

$$X_{rst} \in \Omega(Z_{st}), r = 1,...,R; s = 1,...,S; t = 1,...,T \quad (4)$$

$$\sum_{r=1}^{R} X_{rst} = 1, \ s = 1,...,S; t = 1,...,T \quad (5)$$

$$CC_{s0} = \Psi c(M_{sl}, Th_{sl}), s = 1,..., S \quad (6)$$

$$MC_{rst} = \Psi a(Z_{st}, X_{rst}), r = 1,..., R; s = 1,..., S; t = 1,..., T \quad (7)$$

$$UC_{st} = \Psi u(Z_{st}), s = 1,..., S; t = 1,..., T \quad (8)$$

$$RV_{s,T+1} = \Theta(CC_{s0}, Z_{s,T+1}), s = 1,..., S \quad (9)$$

$$\sum_{r=2}^{R}\sum_{t=1}^{T} X_{rst} \leq N\max_{s}, \forall s = 1,\ldots,S \tag{10}$$

Where: R is the number of alternative M&R operations; S is the number of pavement structures generated for analysis; T is the number of years of the project analysis period; CC_{s0} is the construction cost of a pavement structure s in year 0 in function of the material and thickness of each layer; MC_{rst} is the maintenance cost for applying operation r to pavement structure s in year t; UC_{st} is the user cost for pavement structure s in year t; $RV_{s,T+1}$ is the residual value for a pavement structure in year T+1; X_{rst} is equal to one if operation r is applied to pavement structure s in year t, otherwise it is equal to zero; d is the discount rate; Z_{st} are the condition variables for pavement structure s in year t; $\underline{Z}$ are the warning levels for the condition variables of pavement structures; M_{sl} is the material of layer l of pavement structure s; Th_{sl} is the thickness of layer l of pavement structure s; $N\max_s$ is the maximum number of M&R operations that may occur in pavement structure s over the project analysis period; Φ are the pavement condition functions; Θ are the residual value functions; Ψc are the construction cost functions; Ψa are the agency cost functions for M&R; Ψu are the user cost functions; Ω are the feasible operations sets.

Equation (1) expresses the minimisation of total discounted costs over the project analysis period, while keeping a pavement structure above specified quality standards. Total costs include construction costs, M&R costs, user costs and the residual value of a pavement structure, i.e. its value at the end of the project analysis period. Constraints (2) correspond to the pavement condition functions, expressing pavement condition in each year as a set of functions of the initial pavement state and the M&R operations previously applied to the pavement. These functions can describe the pavement condition with regard to variables such as cracking, rutting, longitudinal roughness, surface disintegration (potholing and ravelling) and overall quality of pavements, etc. In Portugal, the Pavement Management System (PMS) of the Portuguese Road Administration (Picado-Santos and Ferreira 2008, Ferreira *et al*. 2011), and other municipal PMS (Ferreira *et al*. 2009a, Ferreira *et al*. 2009b), uses the pavement performance model of the flexible pavement design method developed by the American Association of State Highways and Transportation Officials (AASHTO 1993) to predict the future quality of pavements. Thus, this application of the LCCA system will consider the AASHTO flexible pavement design method. The basic design equation used for flexible pavements is Equation (11) which can be transformed into Equation (12) to be directly used in the prediction of the present serviceability index value in each year of the design period. Equation 13 is used to calculate the SN value for each pavement structure. Equation (14) is used to compute the number of 80 kN equivalent single axle load (ESAL) applications until any year of the project analysis period.

$$\log_{10}(W_{80}) = Z_R \cdot S_0 + 9.36 \cdot \log_{10}(SN+1) - 0.2 + \frac{\log_{10}\left[\dfrac{\Delta PSI}{4.2-1.5}\right]}{0.40 + \dfrac{1094}{(SN+1)^{5.19}}} + 2.32 \cdot \log_{10}(M_R) - 8.07 \tag{11}$$

$$PSI_t = PSI_0 - (4.2-1.5) \times 10^{\left[\left(\log_{10}(W_{80_t}) - Z_R \times S_0 - 9.36 \times \log_{10}(SN_t+1) + 0.2 - 2.32 \times \log_{10}(M_R) + 8.07\right) \times \left(0.4 + \frac{1094}{(SN_t+1)^{5.19}}\right)\right]} \tag{12}$$

$$SN = \sum_{l=1}^{L} H_l \times C_l^e \times C_l^d \tag{13}$$

$$W_{80_t} = 365 \times AADT_h \times \frac{(1+g_h)^{Y_t} - 1}{g_h} \times \alpha \tag{14}$$

Where: W_{80} is the number of 80 kN equivalent single axle load applications estimated for a selected design period and design lane; Z_R is the standard normal deviate; S_0 is the combined standard error of the traffic prediction and performance prediction; ΔPSI is the difference between the initial or present serviceability index (PSI_0) and the terminal serviceability index (PSI_t); SN is the structural number indicative of the total required pavement thickness; M_R is the sub-grade resilient modulus (pounds per square inch); C_l^e is the layer (structural) coefficient of layer l; C_l^d is the drainage coefficient of layer l; and H_l is the thickness of layer l; PSI_t is the Present Serviceability Index in year t; PSI_0 is the Present Serviceability Index of a pavement immediately after construction (year 0); W_{80_t} is the number of 80 kN equivalent single axle load (ESAL) applications in year t (million ESAL/lane); SN_t is the structural number of a pavement structure in year t; $AADT_h$ is the annual average daily heavy traffic in the year of construction or the last rehabilitation, in one direction and per lane; g_h is the annual average growth rate of heavy traffic; Y_t is the time since the construction of the pavement or its last rehabilitation (years); α is the average heavy-traffic damage factor or simply truck factor.

Constraints (3) are the warning level constraints which define the maximum (or in relation to the *PSI*, the minimum) level for the pavement condition variables. The warning level adopted in this study considering the AASHTO pavement design method was a PSI value of 2.0 which corresponds to the PSI terminal value for national roads. A corrective M&R operation appropriate for the rehabilitation of a pavement structure must be performed when the PSI value is lower than 2.0. Constraints (4) represent the feasible operation sets, i.e. the M&R operations that can be applied to maintain or rehabilitate the pavement structure in relation to its quality condition. In this study two M&R operations will be considered (Table 1). The M&R operation 1, that corresponds to "do nothing", is applied to a pavement structure if the PSI value is above the warning level; that is, if the PSI value is greater than 2.0. The M&R operation number 2 is the operation that must be applied to a pavement structure when the warning level is reached; that is, this operation is applied to rehabilitate the pavement structure. The M&R operation costs, in the same way as the construction costs, were obtained from the PMS of the Portuguese road administration and correspond to the 85th percentile.

Table 1. Maintenance and rehabilitation operations

M&R operation	Description	Cost	M&R actions involved	Cost
1	Do nothing	€0.00/m^2	No actions	€0.00/m^2
2	Structural rehabilitation	€21.29/m^2	Wearing layer (5 cm)	€6.69/m^2
			Tack coat	€0.41/m^2
			Base layer (10 cm)	€8.63/m^2
			Tack coat	€0.41/m^2
			Membrane anti-reflection of cracks	€1.88/m^2
			Tack coat	€0.41/m^2
			Surface levelling (2 cm)	€2.45/m^2
			Tack coat	€0.41/m^2

Constraints (5) indicate that only one M&R operation should be performed per pavement structure in each year. Constraints (6) represent the construction costs, which are computed in relation to the material and thickness of each pavement layer. Constraints (7) represent the M&R costs, which are computed in relation to the pavement condition and the M&R operation applied to the pavement in a given year. Constraints (8) represent the user cost functions. They express the costs for road users as a function of the pavement condition in a given year. Equation (15) was adopted for calculating the user costs because it is already used in some Portuguese PMS for calculating this type of costs (Ferreira *et al*. 2009b).

$$UC_t = 0.39904 - 0.03871 \times PSI_t + 0.00709 \times PSI_t^2 - 0.00042 \times PSI_t^3 \quad (15)$$

Where: UC_t are the user costs in year t (€/km/vehicle); PSI_t is the Present Serviceability Index in year t.

Constraints (9) represent the residual value functions. They express the value of the pavement structure at the end of the project analysis period as a function of the construction cost and the pavement condition at that time. Equation (16) is used for calculating the residual value of pavements structures, which is also used in Portuguese PMS for the same purpose. Constraints (10) were included in the model to avoid frequent M&R operations on the same pavement structure.

$$RV_{T+1} = CC_0 \times \frac{PSI_{T+1} - 1.5}{4.5 - 1.5} \quad (16)$$

Where: RV_{T+1} is the residual value for a pavement structure in year T+1; CC_0 is the construction cost of a pavement structure in year 0 depending on the material and thickness of each layer; PSI_{T+1} is the Present Serviceability Index in year T+1.

3. Case Study

3.1. Introduction

In the Portuguese manual (JAE 1995), a pavement structure is recommended depending on traffic class, which varies between T1 and T6, and pavement foundation class, which varies between F1 and F4. The traffic class is defined by the number of 80 kN equivalent single axle load (ESAL) applications for a design life or design period calculated in relation to the annual average daily heavy-traffic ($AADT_h$), the annual average growth rate of heavy-traffic (g_h) and the average heavy-traffic damage factor or, simply, truck factor (α). On the other hand, the pavement foundation class is defined by the California bearing ratio (CBR) value and the design stiffness modulus (E). The Portuguese manual considers 16 different flexible pavement structures for different combinations between traffic and pavement foundation. These pavement structures were defined using the Shell pavement design method (Shell 1978), with verification by using the University of Nottingham (Brunton *et al*. 1987) and Asphalt Institute (AI 2001) pavement design methods. In order to compare different solutions in terms of global costs for the final choice of the pavement structure for a national road or highway, the OPTIPAV system was applied to 384 combinations of traffic (6 different values), foundation (4 different values of the foundation stiffness modulus) and pavement structure (16 different flexible pavement structures) using a total costs optimization approach. The objective of this analysis is to select the pavement structure that minimizes net present value (NPV), calculated by adding the construction costs, the annual maintenance costs, the annual user costs and deducting the residual value of pavements at the end of the project analysis period, while always keeping the pavements PSI value above the warning level of 2.0. In this application of the OPTIPAV system the following statistic design values were considered: a Z_R value of -1.282 and a S_0 value of 0.45.The economic analysis was done using a discount rate equal to 3%.

3.2. Results of the application of the OPTIPAV System

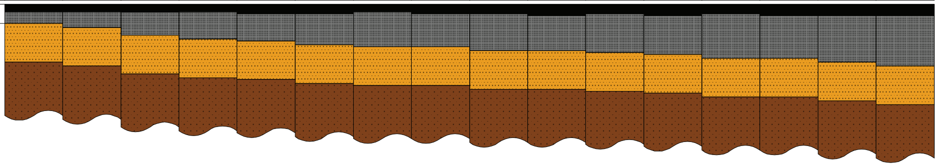
The results presented in this paper were obtained using the following data and conditions: two traffic classes (T1 and T5) characterized in Table 2; one type of pavement foundation (F3 with CBR equal to 20% and design stiffness modulus equal to 100 MPa); sixteen different pavement structures with the characteristics presented in Figure 1; a project analysis period of 40 years. Table 2 also shows the pavement structure recommended in the Portuguese manual for traffic class T5 and pavement foundation F3 (P4) and for traffic class T1 and pavement foundation F3 (P14). Figure 1 presents the characteristics of the pavement structures (type of material, thickness, stiffness modulus; Poisson's ratio, CBR, etc.) that were considered in the pavement design process using the Shell and the other two pavement design methods to define the Portuguese manual of pavement structures. Figure 2 shows the construction costs of each pavement structure. We can see that their values increase with the pavement structural capacity defined by the structural number (SN) considered in the AASHTO pavement design method. Figure 2 also presents the M&R costs during the entire project analysis period for the sixteen pavement structures and for traffic classes T5 and T1. As expected, the M&R costs decrease with the pavement structural capacity, and for traffic class T1 the least-M&R-costs pavement structure is P16. For traffic class T5 there are several pavement structures (P6 to P16) with no M&R costs during the 40 years of the project analysis period. For traffic class T1, pavement structure P9 presents less M&R costs than pavement structures P10 and P11, which would not be expected. The explanation for this can be detected analyzing the rehabilitation operations and the evolution of the PSI value. Figure 3 represents the predicted PSI value over the years of the project analysis period, for each pavement structure and traffic classes T5 and T1, as a consequence of the execution of the rehabilitation operations. It can be seen that the rehabilitation operation is applied when the PSI value reaches its minimum quality value, i.e. 2.0. Figure 3 shows, as expected, that for the lowest traffic class (T5) and for all pavement structures the degradation of the PSI value during the project analysis period is slower than for the highest traffic class (T1). They also show that using weak pavement structures (with a small SN value) the PSI value decreases quickly in the first years of the project analysis period. Then with the application of M&R operations the PSI value decreases slowly in the remaining years of the project analysis period because the SN increases, making these pavement structures stronger. For traffic class T5, if pavement structure P4 recommended by the Portuguese manual is adopted then only one rehabilitation operation will be needed in the 34th year of the project analysis period. For traffic class T1, if pavement structure P14 recommended by the Portuguese manual is adopted then again only one rehabilitation operation will be needed, but in this case in the 20th year of the project analysis period. This pavement structure will not require any rehabilitation operation during 20 years, the design period considered in the Portuguese Manual.

Table 2. Traffic classes and corresponding values

Traffic					Pavement foundation			Pavement structure
Traffic class	$AADT_h$	g_h (%)	α	ESAL (20 years)	Foundation class	E (MPa)	ν	Manual
T5	300	3	3	0.88×10^7	F3	100	0.35	P4
T1	2,000	5	5.5	13.28×10^7	F3	100	0.35	P14

Layer	Property	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14	P15	P16
		Flexible Pavement Design Alternatives															
HMA Surface Layer	Thickness (cm)	4	4	4	4	5	5	4	5	5	6	5	6	5	6	6	6
	Stiffness Modulus (MPa)	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000
	Poisson´s ratio	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
	Material	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC
HMA Base Layer	Thickness (cm)	6	8	12	14	14	16	18	17	19	18	20	20	23	22	24	26
	Stiffness Modulus (MPa)	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000	4000
	Poisson´s ratio	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
	Material	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC	AC
Sub-base Layer	Thickness (cm)	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20
	Stiffness Modulus (MPa)	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200
	Poisson´s ratio	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
	Material	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G
Sub-grade	Thickness (cm)	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
	Stiffness Modulus (MPa)	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
	Poisson´s ratio	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
	CBR (%)	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20
Total HMA Layer Thickness (cm)		10	12	16	18	19	21	22	22	24	24	25	26	28	28	30	32
Structural Number		2.36228	2.63000	3.16544	3.43316	3.60639	3.87411	3.96860	4.00797	4.27569	4.31506	4.40955	4.58278	4.81113	4.85050	5.11822	5.38594

Illustration:



Key: AC - Asphalt Concrete; G - Granular Material; CBR - California Bearing Ratio; HMA - Hot Mix Asphalt

Fig. 1. Characteristics of pavement structures

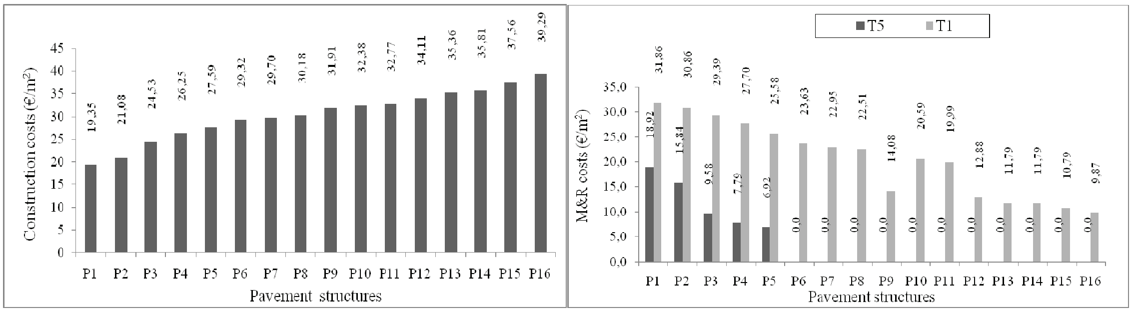


Fig. 2. Construction costs of pavement structures and M&R costs throughout the project analysis period

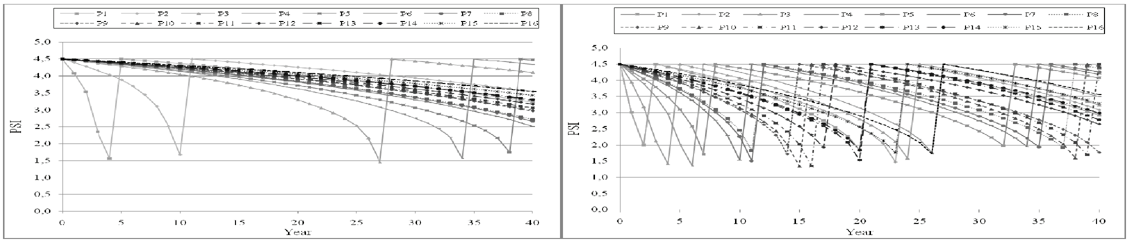


Fig. 3. Evolution of PSI for each pavement structure and traffic class T5 (left) and Traffic class T1 (right)

Figure 4 presents the total user costs throughout the project analysis period and also the residual value at the end of the project analysis period corresponding to traffic classes T5 and T1. It shows that the total user costs are much higher for traffic class T1 than for traffic class T5, but for the same traffic class all the pavement structures have relatively close values. The difference between the maximum and the minimum user costs is 0.68% and 0.60% for T5 and T1 traffic classes, respectively. Taking the traffic class T5 and pavement structure P4 as a reference, the total user costs are approximately 915% higher when the traffic category is T1. This happens because the difference between traffic volumes is enormous, and the degradation of PSI value is higher for traffic class T1. Figure 5 presents the Net Present Value (NPV) and the highway agency costs for each pavement structure for both traffic classes T5 and T1. Considering the NPV, the results show that the optimum pavement structure for traffic class T5 (P13) is different from the pavement structure recommended by the Portuguese manual of pavement structures (P4), although for traffic class T1 the OPTIPAV system and the Portuguese manual recommend the same pavement structure (P14). Considering traffic class T5, P13 is the least-total discounted costs pavement structure, allowing savings of €4.81 per m^2 (approximately 0.32%) comparatively to P4, which is the pavement structure recommended by the Portuguese manual. For example, for a road with 100 kilometres long and 10 meters wide it corresponds to a saving of €4,810,000.00. Considering only costs directly related to a highway operator or highway agency, i.e. constructions costs, M&R costs and the residual pavement of pavement structures, we can conclude that pavement structure P5 is the optimum pavement structure for traffic class T5, while pavement structure P16 is the optimum pavement structure for traffic class T1. For example, pavement structure P5 has the following values: construction costs (€27.59/m^2); maintenance costs (€6.92/m^2); residual value (€8.62/m^2). Pavement structure P4 has the following values: construction costs (€26.25/m^2); maintenance costs (€7.79/m^2); residual value (€7.85/m^2). We can see that P5 has higher construction costs (more €1.34/m^2) but lower maintenance costs (less €0.87/m^2) and a higher residual value (more €0.77/m^2). Considering these costs, P5 allows savings of €0.3 per m^2. For a road with 100 kilometres long and 10 meters wide it corresponds to a saving of €300,000.00.

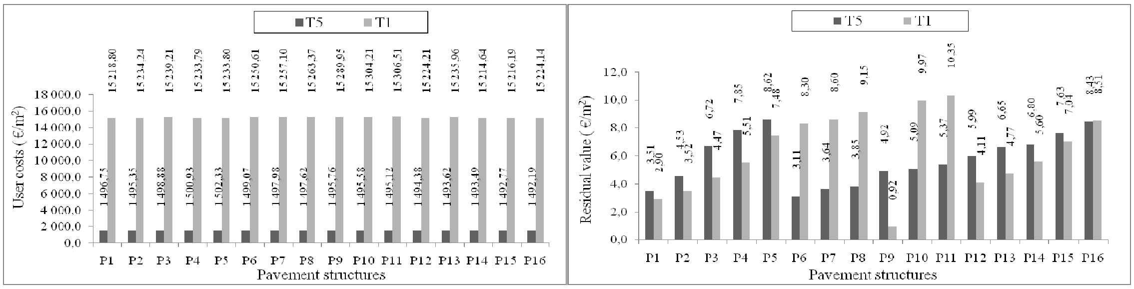


Fig. 4. User costs throughout the project analysis period and residual value at the end of the project analysis period

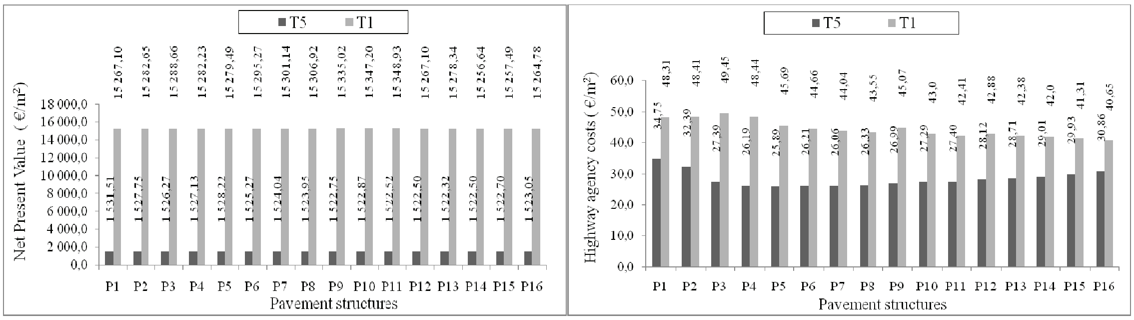


Fig. 5. Net Present Value and highway agency costs for each pavement structure

Table 3 presents the pavement structures recommended by the Portuguese manual and the optimum pavement structures defined by using the OPTIPAV system considering all the costs and considering only the highway agency costs. Considering all the costs, one can see that in eight cases the optimum pavement structure defined by using the OPTIPAV system has more structural capacity, in four cases it has the same structural capacity, and in six cases it has less structural capacity. The pavement structures recommended by the Portuguese manual and by the OPTIPAV system are different in 78% of the cases. Considering only the highway agency costs, one can see that in thirteen cases the optimum pavement structure defined by using the OPTIPAV system has more structural capacity, in five cases it has the same structural capacity, and in no case it has less structural capacity. In the most cases, pavement structures with more structural capacity allow for savings in terms of highway agency costs.

Table 3. Optimum pavement structures

Traffic class	AADT	$AADT_h$	g_h (%)	α	ESAL (20 years)	Pavement foundation	Pavement (Manual)	Pavement (OPTIPAV)	
								Min (NPV)	Min (Agency Costs)
T6	1500	150	3	2	$0.29x10^7$	F1	NAF	P14	P16
T5	3000	300	3	3	$0.88x10^7$	F1	NAF	P16	P16
T4	5000	500	4	4	$2.17x10^7$	F1	NAF	P6	P16
T3	8000	800	4	4.5	$3.91x10^7$	F1	NAF	P15	P16
T2	12000	1200	5	5	$7.24x10^7$	F1	NAF	P16	P16
T1	20000	2000	5	5.5	$13.28x10^7$	F1	NAF	P9	P16
T6	1500	150	3	2	$0.29x10^7$	F2	P3	P13	P7
T5	3000	300	3	3	$0.88x10^7$	F2	P7	P7	P15
T4	5000	500	4	4	$2.17x10^7$	F2	P11	P13	P16
T3	8000	800	4	4.5	$3.91x10^7$	F2	P13	P16	P16
T2	12000	1200	5	5	$7.24x10^7$	F2	P15	P7	P15
T1	20000	2000	5	5.5	$13.28x10^7$	F2	P16	P14	P16
T6	1500	150	3	2	$0.29x10^7$	F3	P2	P3	P3
T5	3000	300	3	3	$0.88x10^7$	F3	P4	P13	P5
T4	5000	500	4	4	$2.17x10^7$	F3	P6	P16	P11
T3	8000	800	4	4.5	$3.91x10^7$	F3	P9	P6	P15
T2	12000	1200	5	5	$7.24x10^7$	F3	P12	P11	P16
T1	20000	2000	5	5.5	$13.28x10^7$	F3	P14	P14	P16
T6	1500	150	3	2	$0.29x10^7$	F4	P1	P1	P1
T5	3000	300	3	3	$0.88x10^7$	F4	P3	P3	P3
T4	5000	500	4	4	$2.17x10^7$	F4	P5	P16	P5
T3	8000	800	4	4.5	$3.91x10^7$	F4	P8	P16	P10
T2	12000	1200	5	5	$7.24x10^7$	F4	P10	P7	P13
T1	20000	2000	5	5.5	$13.28x10^7$	F4	P12	P9	P16

4. Conclusions

The LCCA system for pavement management at project level proposed in this paper, called OPTIPAV, can solve the problem of making LCCA for typical design periods (20 years) but also for longer periods

(40 years or more), in order to compare different pavement solutions in terms of global costs for the final choice of the pavement structure for a national road or highway. Additionally, the OPTIPAV system provides a good solution to the pavement design problem considering not only design criteria but also construction costs, maintenance costs, user costs and the residual value of pavement structures. The application of the OPTIPAV system to the case study allows us to conclude that the pavement structures recommended by the Portuguese Manual are not always the optimum solutions. The pavement structures recommended by the Portuguese manual and by the OPTIPAV system are different in 78% of the cases. The OPTIPAV system already constitutes a useful tool to help road engineers in their task of pavement design. They can now carry out LCCA taking into account any combination of construction costs, maintenance costs, user costs and the residual value of pavement structures, in order to compare different pavement solutions for the final choice of the optimum pavement structure for a national road or highway.

Acknowledgements

The authors are grateful to the Portuguese Foundation of Science and Technology for the financial support provided to this study through Grant PTDC/ECM/112775/2009 - MODAT - Multi-Objective Decision-Aid Tool for Highway Asset Management, financed by the European Community Fund FEDER.

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